Fabrication of a MEMS Comb Drive Actuator

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Abstract— Comb drives are common in many microelectromechanical systems (MEMS) applications such as gyroscopes, accelerometers and resonators in different fields such as optical communication, wireless communication, and biomedical engineering. A comb drive actuator uses electrostatic forces between the combs to create capacitive actuation. The goal of these devices was to achieve a maximum displacement of the movable combs with the lowest amount of drive voltage. Comb drive actuators were designed and then fabricated. It was found that comb fingers were not defined properly as the fingers were either too skinny or have been completely destroyed. This was due to the STS etcher being down in the SMFL and using the Drytek Quad for the mechanical poly etch.

1. Introduction

Comb drive actuators are common in many MEMS applications that require electrostatic actuation. Applications of these devices include micro grippers, gyroscopes, resonators, and voltmeters in various fields like optical communication, wireless communication, and biomedical engineering. Comb drive actuators are capacitive actuators that uses electrostatic forces between two combs. These devices uses electrostatic forces and mechanical restoring forces to actuate. The main goal is to optimize these actuators to get the maximum displacement between the combs with the lowest amount of voltage applied.

Comb drive actuators consist of two combs: one is fixed so that a DC voltage can be applied to create the electrostatic forces and the other which is the part of the device that actuates or moves. The voltage is applied to the anchored comb which creates a displacement between the movable comb fingers and the fixed comb fingers. The basic set up of a simple comb drive actuator is represented in Figure 1. Two main parameters affect the displacement of the comb drive actuator: the spring structure and the driving voltage. Understanding this, a device will be designed using the processes in the SMFL to create a successful comb drive actuator that will move a significant amount while applying a reasonable drive voltage.

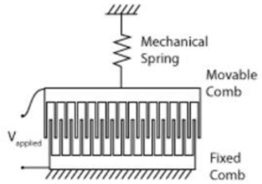

Figure 1: Simple Comb Drive Actuator[1]

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2. Theory

To provide the necessary force to actuate the comb drive actuator, a voltage is applied to the combs. This creates the electrostatic forces that actuate the device. To understand this force, the fingers of the combs are observed.

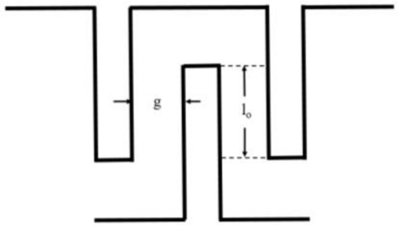

Figure 2: Comb Fingers Detail

Figure 2 shows the important parameters of the comb fingers. g is the gap between the fingers and l_o is the length of the overlap between the fingers. Using these parameters, the capacitance C of one finger is found to be:

$$C = 2\varepsilon_0 \frac{l_0 h}{g} \tag{2}$$

where h is the thickness of the comb drive actuator and ε_0 is the permittivity of free space. To find the total capacitance of the comb drive, simply multiply the capacitance by the number of fingers, n.

The energy stored in a capacitor E is known as the following:

$$E = \frac{1}{2} C V^2 \tag{3}$$

where V is the voltage applied to the capacitor. Since C is found, the known capacitance is inputted to equation (3):

$$E = n\varepsilon_0 \frac{l_0 h}{g} V^2 \tag{4}$$

When the voltage is applied to the comb drive, the movable comb will move a distance x away from the fixed comb. This will change the overlap length of the fingers from l_o to $l_o + x$ and is applied to equation (4):

$$E = n\varepsilon_0 \frac{(l_0 + x)h}{g} V^2 \tag{5}$$

To find the electrostatic force F_e, the derivative of the energy E is taken in respect to x:

$$F_e = \frac{dE}{dx} = \frac{n\varepsilon_0 h}{g} V^2 \tag{6}$$

In equilibrium, the electrostatic force is balanced by the mechanical restoring force of the spring, F_s:

$$F_s = k_x \cdot x = \frac{2Ehb^3}{L^3} \cdot x \tag{7}$$

where k_x is the spring constant, E is Young's modulus, b is the width, and L is the length. The restoring force of the spring in Equation (7) is represented by Hooke's law. Since the system is in equilibrium, an equation for displacement x can be created in terms of voltage V:

$$x = \frac{n\varepsilon_0 L^3}{2Egb^3} V^2 \tag{8}$$

Using Equations (7) and (8), the following plots below show how the force on the comb drive actuator and the displacement of the movable combs are affected by the drive voltage.

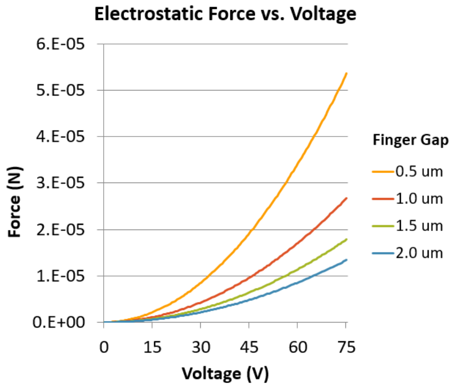

Figure 3: Drive Voltage vs Electrostatic Force Plot for a Drive Actuator

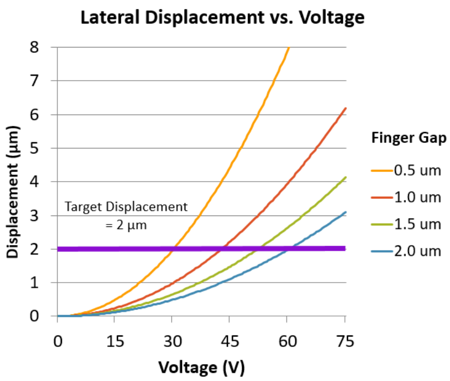

Figure 4: Drive Voltage vs Lateral Displacement Plot for a Comb Drive Actuator

Figures 3 and 4 assumes that the number of fingers are 50, the spring length is 200 um, the spring width is 5 um and the device thickness is 2 um. These parameters are kept constant when changing the gap between the fingers in the comb drive. The plots show as the voltage applied to the combs increase, the electrostatic force and lateral displacement increase exponentially. The plots also show that decreasing the gap between the fingers will also increase the lateral displacement and electrostatic force of the combs.

In the fall semester, two device design were created. The goal of these comb drive actuators were to apply a reasonable sized voltage to get a lateral displacement of 2 um. The designs are labeled Design A and Design B. Design A was made to be the "riskier" design while Design B was made to be the "safer" design. The reason for this is to make sure that if Design A does not work, Design B will work but it is sacrificing the low drive voltage. The table below shows the parameters of each design:

	Design A	Design B
# of Fingers, *n*	47	41
Beam Length, *L*	280 um	200 um
Beam Width, *b*	5 um	5 um
Thickness, *h*	2 um	2 um
Finger Gap, *g*	1.5 um	2 um
Drive Voltage to Move 2um, *V*	52.2 V	92.7 V

Table 1: Design A and B Device Parameters

Using these parameters the device design was created on IC Layout shown below:

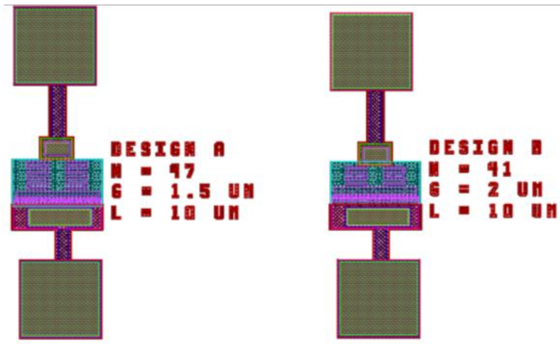

Figure 5: Design Layout of Design A and B

For the spring semester, devices were improved upon by changing the mechanical structure of the springs and the gap between the fingers. To get lower drive voltage on the comb drive actuators, the gap between the fingers of the combs were decreased to 1 um and 0.5 um. In the bottom two rows of the set of devices below in Figure 6, shows the 1 um devices and the 0.5 um devices. For the changes of the mechanical structures of the device, the structure of the springs were altered. For the devices in the third column of the devices in Figure 6, the springs were adjusted so it creates a more stable device. In the last column of devices, only one spring is attached to the comb drive so it requires less drive voltage to move the combs.

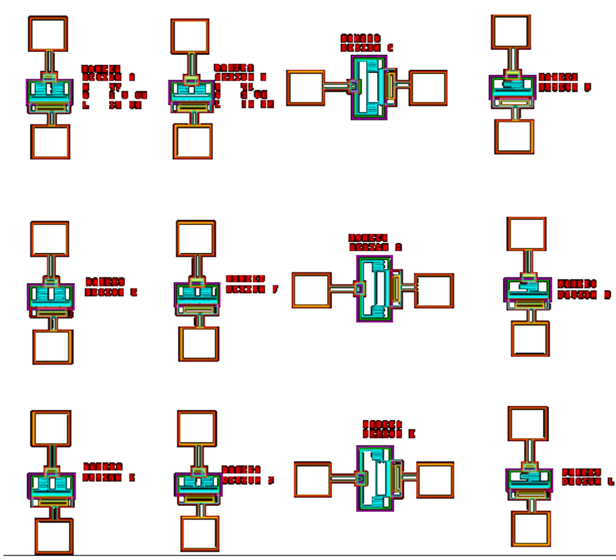

Figure 6: Comb Drive Actuator Designs A-L from the Spring Semester Wafers

3. Procedure

For the MEMS fabrication, the Surface MEMS Fabrication Process 2015 by Dr. Fuller is used. This process has 9 levels [2]:

1. Zero Marks
    a. Photolithography
    b. Zero Etch
    c. Resist Strip
    d. RCA Clean
2. Poly 1
    a. 6500 A Wet Oxide
    b. 5000 A LPCVD Poly
    c. P31 Implant
    d. Photolithography
    e. Poly Etch
    f. Resist Strip
    g. RCA Clean
3. Anchor
    a. 700 A Dry Oxide
    b. LPCVD Nitride 4000 A
    c. Photolithography
    d. Nitride Etch
    e. Resist Strip
    f. RCA Clean
4. Sacrificial Oxide Define
    a. TEOS Oxide 1.75 um
    b. Photolithography
    c. Oxide Wet Etch
    d. Resist Strip
    e. RCA Clean
5. No Implant
    a. LPCVD Poly 2um
    b. Photolithography
    c. P31 Ion Implant
    d. Resist Strip
    e. RCA Clean
6. Poly 2
    a. 500 A Pad Oxide
    b. 2000 A LPCVD Nitride
    c. Photolithography
    d. Nitride Plasma Etch
    e. Pad Oxide Wet Etch
    f. DRIE Etch Poly 2
    g. Resist Strip
7. Contact Cut
    a. Nitride Contact Etch
    b. Oxide Contact Etch
    c. Resist Strip
    d. RCA Clean
8. Metal
    a. Al Metal Deposition
    b. Photolithography
    c. Metal Wet Etch
    d. Resist Strip
9. Release
    a. Work In Progress

The process is still a work in progress since Dr. Fuller and Adam Wardas is working on how to go about the release layer.

Testing for this device will require a power supply to sweep a voltage from 0 V to 100 V. To test, place a positive probe to the top of the device and the bottom probe to the bottom. If the device moves up and down, it is a successful device. To measure how much the comb drives move, the Wyco Optical Interferometer will be used. Using this tool, the measurement of the displacement will be taken at every five volts and plotted to compare to the simulated results.

4. Discussion of Results

Many issues were encountered when fabricating these devices using the RIT Surface MEMS process. The first issue was the anchor level lithography. The anchor lithography was incorrectly performed by inputting the wrong dose and focus which created leftover films during the anchor nitride etch found in Figure 7. Weeks were spent trying to figure out how to remove this films in these areas but it was decided to move on with the rest of the process.

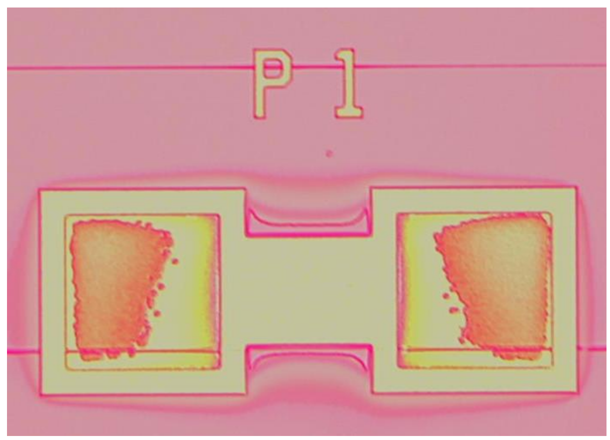

Figure 7: Leftover Film after Anchor Nitride Etch in Pads of Test Structure

Another issue that was found was the sensitivity of the poly 2 lithography step. The first run through of the poly 2 lithography was found that the holes for the sacrificial oxide layer for the release step were not cleared. To fix this a focus exposure matrix was done to find the optimal dose and exposure to clear the holes for the resist. Figure 8 shows the focus exposure test as the matrix goes from a focus of -3.0 um to +3.0 um and an exposure of 280 mJ/cm^2 to 520 mJ/cm^2. By looking at various holes throughout the matrix, it was found that the optimal focus and exposure was -0.5 um and 400 mJ/cm^2. Figure 9 represents examples of the holes that were observed throughout the matrix. When this optimal set up was used, the clearance of the holes were successful.

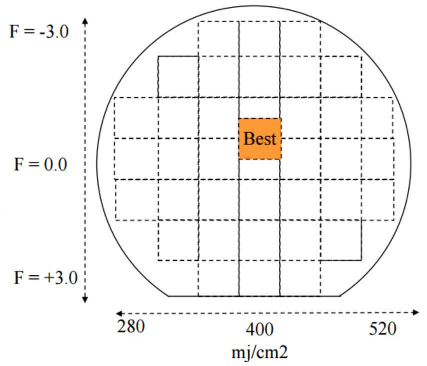

Figure 8: Focus Exposure Test on Control Wafer [3]

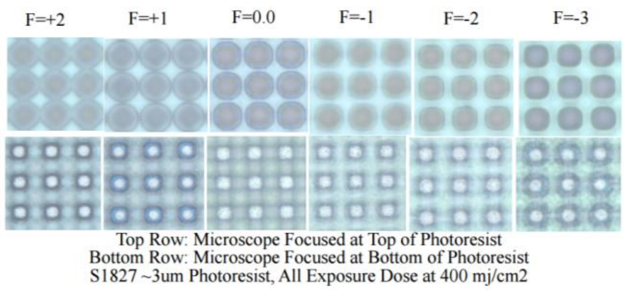

Figure 9: Holes at Varying Focuses to Find Optimal ASML Stepper Setup [3]

The main issue that was found for the combs was the poly 2 etch. During the time fabricating the devices in the fall and the spring, the main tool for the poly 2 etch, STS etcher, was down. The STS Etcher is used as a deep reactive-ion etching (DRIE) tool in RIT using the Bosch process. The Bosch process is a pulse etch that alternates between two modes: a standard isotropic plasma etch and a deposition of a chemically inert passivation layer. Each mode lasts several seconds and as the plasma bombards with the substrate, the ions attack the bottom of the trench and not the sidewalls creating an anisotropic etch. Since the STS etcher was down, the next best option was to use the Drytek Quad. Since the Drytek Quad is just a reactive-ion etching (RIE) tool, the etch was more isotropic and either over-etched the width of the comb fingers or completely destroyed it shown in Figure 10. The design calls for a finger width of ~ 2um but the fingers were measured to have a width of 0.5 um. This shows the importance of the STS etcher for geometric features like comb drive actuators. The STS etcher will be used in future RIT MEMS projects.

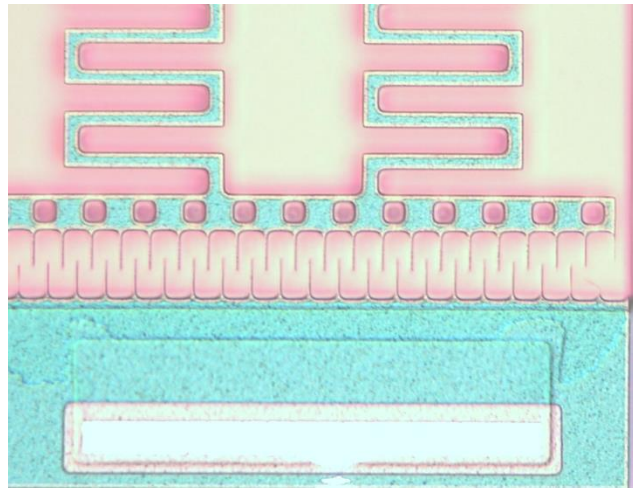

Figure 10: Comb Drive Fingers after Mechanical Poly Etch

Both the fall and springs wafers are not complete. The fall wafers are at the pre-release layer since there are still problems with the release etch. The spring wafers are stuck at metal because the metal etch leave small amounts of aluminum in small features. This problem found in the spring was also found to be the reason why the release etch is not working for the fall wafers. In the future, the metal lithography step will be altered so that the metal etch will be successful in completely etching the unwanted aluminum.

5. Conclusion

Comb drive actuators were designed and partially fabricated using the RIT Surface MEMS process. Improvements were made to the process by finding the optimal focus and exposure for the mechanical poly level. It was also found that the STS etcher was needed to create combs since the Drytek Quad over-etched or completely destroyed the comb fingers. In the future, more improvements can be made to the RIT Surface MEMS process to create successfully MEMS devices.

6. Acknowledgements

Dr. Lynn Fuller
Dr. Robert Pearson
Dr. Dale Ewbank
Mattias Herrfurth
Adam Wardas
Chris O’Connell

7. References

[1] "Introduction to Microelectromechanical Systems (MEMS) | Compliant Mechanisms",*Compliantmechanisms.byu.edu*, 2016. [Online]. Available: https://compliantmechanisms.byu.edu/content/introduction-microelectromechanical-systems-mems. [Accessed: 04- May- 2016].

[2]Fuller, Lynn, “Surface MEMS Fabrication Details”, MEMS Fabrication (MCEE-770)

[3]Fuller, Lynn, “Surface MEMS Fabrication Blog”, MEMS Fabrication (MCEE-770)